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Experimental Validation of PCM Integrated Space Heating

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Highlights

- PCM integrated space heating system is a novel off-grid solution.
- Air is used as the heat transfer medium for keeping the room temperatures in optimum range.
- The results validated the space heating solution by maintaining room temperature above 15 °C.
- For 24 hours, while the ambient varied between 0 and 5 °C, the room temperature was controlled in the range 15-20°C.
- The current system needs aesthetical and functional improvements to be commercialized.

Abstract

Phase change materials (PCM) integrated solar-powered space heating plays a crucial role in maintaining thermal comfort in cold regions where the temperature shoots down to -10 °C. This paper presents the experimental results of using PCM HS22 integrated with solar energy to maintain comfortable conditions inside the experimental prototype in the cold ambient. The solar energy is stored in PCM during the daytime to use it for night-time during off-sunshine hours. The results show that the room temperature is maintained in the 10 to 20 °C temperature range when the ambient was between -10 to 0 °C. The room temperature was maintained consistently for 24 hours.

Keywords: Space heating, Thermal energy storage, Phase change materials, Thermal comfort, Cold climate conditions

Introduction

North India alone consumes 364 million GW of electricity in a year, of which 130 million GW is consumed in extremely cold regions and 260 million GW in moderate climates. It is estimated that 30% of this consumption in moderate climates and 70% in cold areas is due to space heating. Not only in India, but 61% of US homes also depend on electricity-based heating systems, and 69% of Europe's total electricity consumption is because of space heating. About 5000 trillion kWh/year of energy is generated over India's land area. Northern India receives solar insolation of 3-7 kWh/m^2/day.

Solar energy plays an important role in responding to the growing demand for energy as well as dealing with pressing climate change and air pollution issues. Solar energy features low density and intermittency; therefore, an appropriate storage method is required [1]. Thermal energy storage (TES) has become very important in recent years since it balances the energy demand and improves the efficiency of solar systems. Thermal energy storage systems must have the necessary characteristics to improve the performance of the storage systems. The usage of PCMs for energy storage provides a great benefit, but their low thermal conductivity becomes a major drawback. This can be compensated with the use of phase change material in an appropriate design for the effective functioning of the system [2]. The most sensitive parameters affecting the performance of the storage unit are the melting point of the storage material, the mass of PCM, and the airflow rate [3]. The usage of TES for storing energy is a favorable technology that is used in current years[4]. Recently, PCM technology improvement has helped the use of different types of PCMs to increase the energy and exergy efficiency of TES. PCMs can also be incorporated into conventional heating or cooling systems so that their capacity can be reduced. Considerable research has been done on the application of PCMs for space heating and cooling, yet at present, there are limited systems in use [5]. Latent heat thermal energy storage (LHTES) is becoming more and more attractive for space heating and cooling of buildings [6]. The advantage of using space heating in buildings is the ability to store the heat during the day and use it continuously later in the night, particularly in the winter, by reducing diurnal temperature fluctuations.

By avoiding conventional methods for thermal storage, PCMs provide heat storage and nearly constant temperature at much higher energy storage densities. This technology can meet up to a maximum of this demand depending on the region's climate. Active and passive systems are used for this purpose [7]. Both the useful energy and the solar fraction of the system are influenced obviously by the amount of solar radiation. The change in the temperature in the heating room is bigger than that of the contrast as the ambient temperature changes [8].

In this experimental work, the discharging of PCM in a specified fabricated room is presented. This paper gives a clear idea about the feasibility of solar heating systems to achieve stabilization temperatures inside a room. The amount of PCM required, the type of PCM to be used, and the Heat Exchanger (HX) design is the important aspect that this paper clarifies with the experiments performed based on theoretical calculations.

The room-in-room model called the test bed, is set up for the testing of solar space heating experiments. The annular space between the rooms is maintained below -5 °C temperature, and the inner room is heated by the hot convecting air from the ETC. The Solid Works 3D model of the test bed with an ETC has been developed for better visualization.

Materials and Methods

The room-in-room model called the test bed, is set up for the testing of solar space heating experiments. The annular space between the rooms is maintained below -5 °C, and the inner room is heated by the hot convecting air from ETC. The SolidWorks 3D model of the test bed with an ETC collector has been developed for better visualization.

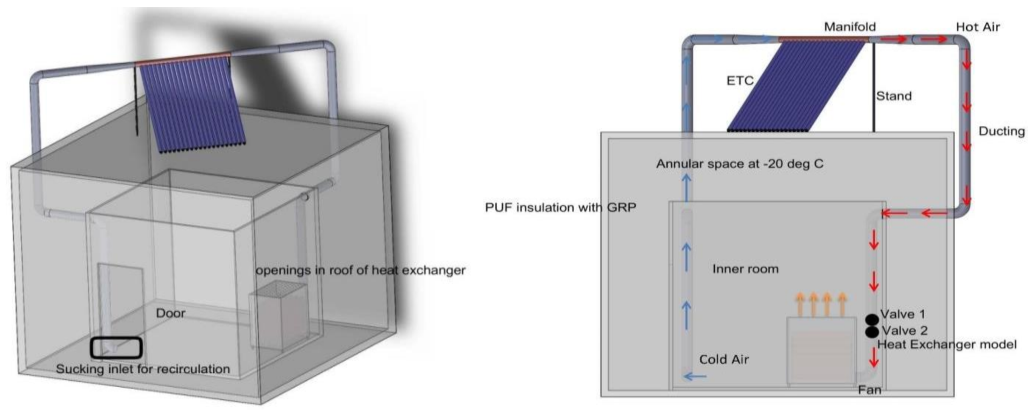

Figure 1: 3D model of test bed (L) Isometric view of model (R) Air flow schematic diagram

The heat transfer from the air to PCM takes place in PCM air HX. The design of the HX is such that the maximum heat transfer takes place by exposing the maximum surface area of the panels to the convecting air. It can accommodate 30 HDPE panels. The insulation is done around the HX to concentrate the incoming heat from the ETC and to prevent heat losses to the room.

Table 1: Test bed specifications

S. No.	Particulars	Specifications
1.	Outer room(mm)	4880x4880x4200
2.	Inner room(mm)	3000x3000x3000
3.	Outer room PUF insulation(mm)	100
4.	Inner room PUF insulation(mm)	60
5.	Inner room and outer room wall material	1.5mm GRP at inner and outer side with PUF insulation
6.	Window (mm)	1000x1000
7.	Window material	Double glazed glass
8.	PVC pipe for ducting(mm)	150Φ
9.	ETC manifold(mm)	100 Φ
10.	ETC manifold material	GI with Aluminum fins

The metal-made roof of the HX is removed and replaced by a foam sheet in which the 5 mm diameter holes are given to exhaust the comparatively less hot air. This is done to increase the residence time of hot air inside HX, which will ultimately increase the heat transfer from the hot air to the PCM panels.

Table 2: HX material specifications

S. No.	Particulars	Specifications
1.	PCM Air HX (mm)	1180x1380x680
2.	HDPE extruded panel (mm)	840x200x20
3.	HX insulation thickness (mm)	25
4.	HX insulation material	Nitrile Rubber Foam
5.	Density of insulation (kg/m^3)	40±2
6.	PCM in each Panel (kg)	3.68
7.	Power capacity of Fan (W)	60
8.	Fan type	Inline Duct fan
9.	PCM type	sav*E*® HS29
10.	Total PCM quantity (kg)	110
11.	Thermocouple type	K-type

Figure 2: (L) PCM air HX closed view (R) Stacking of the HDPE extruded panels inside HX open view

The HX is connected to the ETC of 20 tubes set with the help of ducting. The ducting has been done with a 6” (150 mm) diameter PVC pipe.

Figure 3: (L) ETC solar collector system with ducting (R) PCM air HX with Nitrile rubber foam insulation and dampers to switch the air circulation during night-time.

Figure 4: (L) Inside view of the inner room with HX, fan, data logger, and ducting (R) Sucking inlet of the room air

The air suction is created by inline fans connected from the HX in the room to the ETC. The manifold of the collector is made of GI pipe. The copper heat pipes have been inserted in the manifold to transfer the heat to the flowing air through it. To maximize the contact surface area of the air, aluminum fins were inserted into the manifold. The insertion of the fins improves the heat transfer to the air. Successive experiments are performed to achieve the set target of stabilizing the room in the required temperature range.

First, all the equipment, like the data logger and thermocouples, were calibrated, and then the thermocouples were installed at different locations in the setup. The amount of PCM needed was calculated using thermal calculations, and then the encapsulation of the PCM was decided. After this, the design of the HX model was done.

Table 3: Specifications of savE® HS29.

S. No.	Property	Unit	Value
1	Melting Temperature	℃	29.0
2	Freezing Temperature	℃	26.0
3	Latent Heat Melt	kJ/kg	196
4	Latent Heat Cool	kJ/kg	199
5	Liquid Density	kg/m^3	1540
6	Solid Density	kg/m^3	1651
7	Liquid Specific Heat	kJ/kg K	2.53
8	Solid Specific Heat	kJ/kg K	2.27
9	Liquid Thermal Conductivity	W/mK	0.56
10	Solid Thermal Conductivity	W/mK	1.13

First, U is calculated using Equation 2, and then Equation 1 is used to calculate heat conducted through all surfaces of the inner room. Based on this calculation, the net heat load is calculated using Equation 3. Where Q is the heat transferred, U is the overall heat transfer coefficient, A is the area over which the heat transfer occurs, T is the difference in temperature,

$$Q = U \; X \; A \; X \; \Delta T \quad (1)$$

$$U = \frac{1}{R} = \frac{k}{x} \quad (2)$$

$$Q_{net} = Q \; X \; t \; X \; 3600 \quad (3)$$

A negative sign of Q_{net} shows the heat loss from the system. After calculating the net heat load, the quantity of PCM (m) required is calculated using Equation 4. Cp is the specific heat of the PCM, Ti is the initial temperature of the PCM when the heat transfer was initiated, and Tm is the temperature of melting of the PCM.

$$m = \frac{|Qnet|}{(L + Cp \times (Ti - Tm)) \times 1000} \quad (4)$$

Working of the Test chamber – An inline fan installed at the inlet of the PCM air HX creates suction in the pipe connected with the ETC. The convecting air carries the heat generated by the ETC during a good sunny day. The heat carried by the air passes through the barriers created by the aluminum fins, which are in direct contact with the heat pipes. The aluminum fins are installed inside the ETC manifold to increase the contact surface area of the air to maximize the heat gain. Then, the heated air enters the HX through PVC ducting with a force convecting fan installed at the inlet of the HX. The heated air passes over the PCM panels and charges them for later use. The heat gets accumulates in the HX as the inlet of the air into the HX is from the bottom, and the outlet is provided at the top of it. The outlet velocity of the air from HX is very low as the holes' size is very small, through which it escapes to the room space. The air coming out from HX heats the inner room, along with the remaining heat inside it. This air is then recirculated through an extra opening in the room. This process is repeated during the daytime. During the sunshine hours, damper valve 1 remains open, and valve 2 is closed, as shown in Figure 1. But after sunshine hours, the valves are toggled, and valve 1 and valve 2 remain closed and opened, respectively, till sunrise. During off-sunshine hours, the room air is passed through the HX and gets heated up after coming into contact with charged sav*E*® HS29. The PCM slowly starts discharging till the whole energy of the PCM gets exhausted. The experiments were performed in May month of the year 2018-19. The GHI for this month is 6.65 kWh/m^2/day in the geographical location of Bawal, Haryana (Lat, Lon: 28.05, 76.55).

The thermocouples at the inlet, center, and top of the HX are installed to get an idea of the temperature variations inside it. The thermocouples at the ETC collector inlet and outlet, sucking air outlet pipe, inner room volumetric center point, and an annular space between two rooms are also installed.

Results

The results produced for the complete cycle of the PCM inside the test bed are shown in the figure given below. The testing is done for a full day to check the complete charging and discharging of the PCM.

Figure 5 depicts the temperature variations at different locations in the test bed and the HX for the complete 24 hours. The collector inlet temperature is at 15 °C, and the collector outlet temperature is at 30 °C at the start of the experiment. The collector outlet temperature increases to 50 °C at around 02:00 PM, which is the peak time of the beam solar radiation capturing, and annular space temperature is maintained between 0 to -5 °C during sunshine hours and -10 to -15 °C during off-sunshine hours. The collector inlet temperature varies between 20 °C to 35 °C. The collector inlet and outlet temperatures rose to very high temperatures during off-sunshine hours. This is because valve 1 is closed after sunshine hours, and the diffused radiation of the sun captured in ETC increases the temperatures of the collector, and there is no heat transfer from the collector to HX during off-sunshine hours.

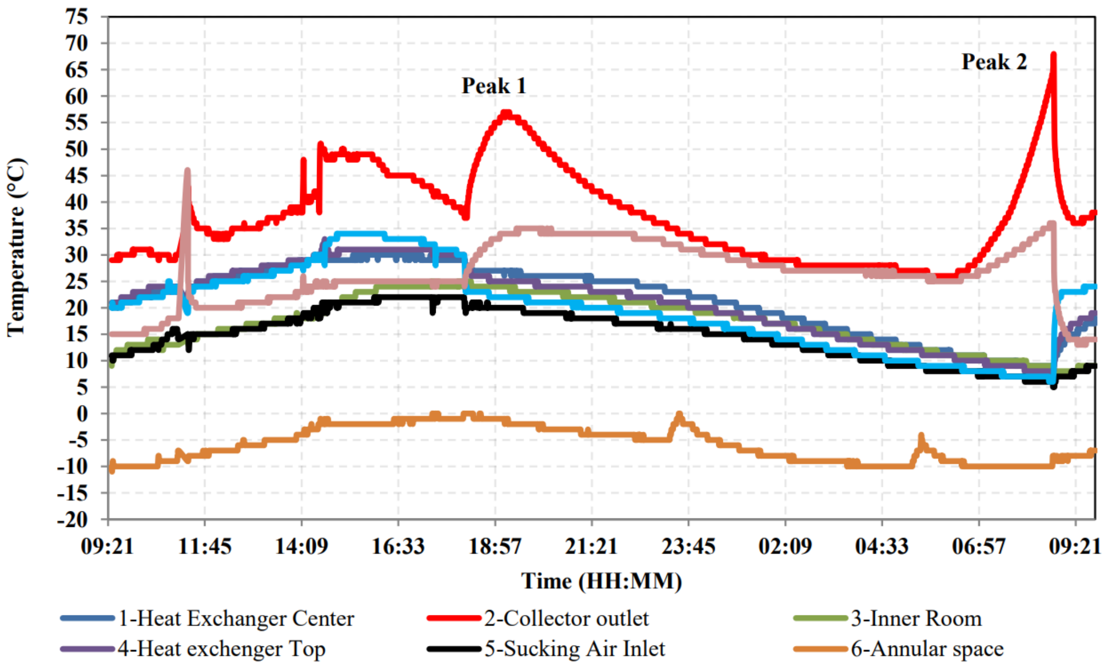

Figure 5: Temperature variations in the inner room and at other locations

The sudden shoot-up of the collector outlet temperature (Peak 1) is due to the solar radiation capturing in the ETC manifold after closing valve 1, which supplies the air from the collector to the room. This results in a rise in collector inlet temperature. Peak 2 is due to the same reason as peak 1, as valve 1 has not been opened till 08:48 AM, which resulted in the rise of the temperature inside the ETC assembly. At the beginning of the experiment, the inner room temperature is around 15 °C and varies between 10 °C to 25 °C temperature for 24-hour span. The inner room temperature is at its maximum of 25 °C at around 05:00 PM, and then it starts decreasing. The room temperature remains above 15ºC till around 05:00 AM and remains between 10-15ºC temperatures for the next 3-4 hours. So, the backup hours for the PCM are approximately 11 hours during off-sunshine hours.

As the temperature at the fan outlet was above 30ºC for more than 4 hours, the PCM melted inside the HX very easily. This molten PCM releases its energy for the next 12 hours and warms up the inner room.

Conclusions

- The results from the scaled-up model indicate that the PCM sav*E*®HS29 is suitable for maintaining room temperature in the range of 15-25 °C.
- The annular space temperature varies from 0 to -5 °C in the daytime and -10 °C to -15 °C at night. During this, the collector outlet temperature varies from 30 °C to 43 °C.
- The temperature is maintained in the required range inside the room till 6 AM and remains between 10-15°C for the next 3-4 hours till the solar collector gets enough radiation that can increase the air temperature above 15°C.
- The heat conducted by the inner room to the annular space maintained at -20°C temperature is balanced by the heat gain in the room through PCM for approximately 12 hours.

The work has not been carried forward because of the installation challenges in the COVID times. The thermal energy storage setup discussed in this paper has the potential to be integrated into Leh. However, there will be several challenges that need to be catered. For example, air density at higher altitudes is low, and hence, heat transfer will be slow. The wind speed has not been simulated in the test chamber. The temperature variation is large in the higher altitudes. To solve all these challenges, some modifications will have to be made to the current setup. To do this, the next step is to undergo simulation studies that take into account the weather conditions at higher altitudes.

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